Geological Quarterly, 2020, **64** (3): 567–588
DOI: http://dx.doi.org/10.7306/gq.1536

# Foraminiferal and calcareous nannoplankton bioevents and changes at the Late Cretaceous–earliest Paleogene transition in the northern margin of Tethys (Hyżne section, Polish Carpathians)

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Machaniec, E., Kowalczewska, O., Jugowiec, M., Gasiński, M.A., Uchman, A.. 2020. Foraminiferal and calcareous nannoplankton bioevents and changes at the Late Cretaceous–earliest Paleogene transition in the northern margin of Tethys (Hyżne section, Polish Carpathians). Geological Quarterly, **64** (3): 567–588, doi: 10.7306/gq.1536

Foraminifera and calcareous nannoplankton from the Cretaceous–Paleogene (K-Pg) transition in the Hyżne section (Outer Carpathians, south-eastern Poland) show a relatively complete biostratigraphic record. Despite the absence of the P Zone in turbiditic deposits of the Polish Carpathians, the planktonic foraminiferal zones of the Late Cretaceous–Early Paleogene interval are well defined, including (1) the late Maastrichtian *Abathomphalus mayaroensis* Zone and its equivalents, (2) the earliest Danian *Guembelitria cretacea* second bloom Zone (P0 Zone), and (3) the top of the early Danian *Parasubbotina* cf. *pseudobulloides* (P1a) Zone. The foraminiferal events recorded in the studied section at the K-Pg transition are stratigraphically important. They include: (1) the interval with *A. mayaroensis* occurrence, (2) the interval with gradual disappearance of planktonic foraminifera from the most complex *K*-strategy forms, through the less specialized species to the large Heterohelicidae turnovers, and (3) the *G. cretacea* first and second blooms. Furthermore, the bloom of the opportunistic, benthic *Bolivinita* sp., the size reduction event, and the dissolution of the tests of the planktonic foraminifera are recorded. The K-Pg interval bioevents can be useful for better stratigraphic resolution of the flysch deposits of the Outer Carpathians. The nannoplankton event is represented by the appearance of *Cruciplacolithus primus,* which marks the onset of the return to more stable environmental conditions after the perturbations at the K-Pg boundary. The K-Pg boundary occurs within dark grey marly mudstones, above the upper boundary of the *G. cretacea* first bloom, and above the highest occurrence of the agglutinated foraminifera *Goesella rugosa,* at the top of the nannofossil CC 26 Zone, and below the deep-water agglutinated foraminifera (DWAF) dominance. The foraminiferal assemblages derive from different bathymetric zones corresponding to (1) the upper bathyal zone in the late Campanian (nannoplankton CC 22 Zone) and early late Maastrichtian (*A. mayaroensis* Zone), (2) the shelf margin in the latest late Maastrichtian (CC 26 nannoplankton Zone, *G. cretacea* first bloom), (3) the shelf margin in the earliest Danian (*G. cretacea* second bloom, NP1/2 Zone), and (4) the middle–lower bathyal depth, below a local foraminiferal lysocline and above CCD, in the latest early Danian (*P. pseudobulloides* Zone). As the foraminifera could have been redeposited by turbiditic currents, they do not necessarily show real bathymetric changes in the area of deposition. Such changes have not been observed in sedimentary features of the studied deposits. Foraminiferal and nannoplankton assemblages are typical of the "transitional zone" between the Tethyan and Boreal domains.

Key words: foraminifera, nannoplankton, bio-events, K-Pg boundary, Skole Nappe, Outer Carpathians.

## INTRODUCTION

The K-Pg transition records one of the largest known mass extinctions in the Earth history. The causes and timing of the K-Pg mass extinction have been the subject of high-resolution investigations during the latest few decades. Most of the studied K-Pg sections worldwide are in the Atlantic and Pacific oceans, and in the southwestern Western Tethys, while sections of the northeastern Western Tethys have been poorly explored (Keller et al., 2011a). Thus, the analysed Hyżne section serves as an important and complementary site in the studies of K-Pg transition of the Polish Outer Carpathians. This transition shows the turbiditic (flysch-type) deposits that accumulated in the northern margin of the Tethys and records the mass extinction pattern and the associated palaeoenvironmental changes.

In turbiditic deposits, the biostratigraphical record is strongly dependent on the palaeoecological preferences of the index taxa and on the taphonomic processes, such as preservation, postmortem transport, mixing of assemblages, and dissolution effects, which must always be taken into consideration. The K-Pg boundary in the turbiditic series is very difficult to identify due to the rare occurrence of index planktonic foraminifera, caused by the frequent dispersion of microfossils in the sedi-

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Received: November 7, 2019; accepted: February 17, 2020; first published online: June 2, 2020

ment, strong redeposition (resedimentation) leading to the occurrence of mixed foraminiferal assemblages, and later tectonic deformations (e.g., Szydło, 2008, and references therein).

The Hyżne section offers the unique opportunity to obtain more precise data by combining different methods of dating such as correlation of the standard planktonic zones with benthic foraminifera (less affected by the environmental changes) and calcareous nannoplankton assemblages. Analysis and correlation of planktonic with both calcareous and agglutinated benthic foraminifera (the last one being considered as the most common type in the Flysch Carpathians) from the investigated section have provided better stratigraphic resolution of the studied deposits, particularly that the Cretaceous–Paleogene agglutinated foraminiferal zonations of Geroch and Nowak (1984) has not been calibrated with the standard planktonic foraminiferal ones (see Olszewska, 1997, and references therein).

The mass extinction pattern was described based on planktonic foraminifera with support of benthic foraminifera which contribute further information about palaeoenvironmental conditions. These data provide a new insight into the nature and origin of the environmental changes that led to the K-Pg mass extinction as recorded on the northern margin of Tethys.

## GEOLOGICAL SETTING

The investigated area is located in the Western Flysch Carpathians, which consist of several overthrust nappes and thrust sheets. One of them, the Skole Nappe, occupies the most external tectonic position in the Polish Outer Carpathians. It is situated on the NE bend of the Carpathian orogenic arc and is bordered by the Stebnik, Zgłobice and Boryslav–Pokuttia units in the north and northeast (Jankowski et al., 2004) and by the Subsilesian Nappe from the south. The Skole Nappe is composed of Lower Cretaceous to Lower Miocene marine deposits that accumulated in the Skole Basin, the infill of which was folded and thrust northward during the Miocene (e.g., Gągała et al., 2012).

A large part of the Skole Nappe sedimentary succession is occupied by the Upper Cretaceous–Paleocene Ropianka Formation (also called the Inoceramian Beds), which is dominated by turbiditic, thin- to thick-bedded deposits composed of alternating sandstones and mudstones or marls, and debris-flow deposits (e.g., Kotlarczyk, 1978, 1979; see also Bromowicz, 1974; Kotlarczyk et al., 1988; Leszczyński et al., 1995; Ślączka and Miziołek, 1995). Kotlarczyk (1978) subdivided the Ropianka Formation into the Cisowa Member (distinguished only in the Cisowa IG 1 borehole, Wdowiarz et al., 1974; Turonian–lower Campanian), the Wiar Member (lower Campanian–lower Maastrichtian), the Leszczyny Member (lower Maastrichtian–lower Paleocene) and the Wola Korzeniecka Member (Paleocene). The deposits studied belong to the Wiar and Leszczyny members. In the latest decade, the Ropianka Formation was a subject of several investigations (e.g., Gasiński and Uchman, 2009, 2011; Kędzierski and Leszczyński, 2013; Gasiński et al., 2013; Salata and Uchman, 2013; Kędzierski et al., 2015; Łapcik et al., 2016; Kowalczewska and Gasiński, 2018; Łapcik, 2018; Waśkowska et al., 2019).

The studied section is located at Hyżne, hamlet Nowa Wieś (GPS coordinates of the section 49°55.995'N; 22°10.551'E; ±8 m; Fig. 1B), ~25 km SE of the city of Rzeszów. The section crops out (natural outcrop) along an unnamed stream and its right tributary. It is composed of turbiditic calcareous sandstones, calcareous siltstone, mudstone shales and dispersed marlstone beds (Fig. 2). The lower part of the section (intervals A1, A2 and B) contains more marlstones and marly shales, apart from the middle part of interval A2, where sandstone beds dominate, up to 2 m thick. The interval C is built of dark grey marly mudstones. The uppermost part of the section (intervals C, D), contains marlstones with very low contribution of thin sandstone beds.

## MATERIAL AND METHODS

The fieldwork was conducted on the Hyżne section (Fig. 1) along a 591 m thick section of the Ropianka Formation. Twenty-seven samples were collected from marls and marly mudstones (Hy1–Hy13 and Hn1–Hn14), and from the hard marls and mudstones eight thin sections were prepared for palaeoecological and biostratigraphical analyses. The samples were taken from the $T_e$ part of the turbiditic sequences. For the analysis of foraminifera, 400 g samples were processed in the laboratory, using the conventional method of disintegration (heating and freezing in Glauber's salt). After disaggregation, the samples were washed through a set of sieves. Quantitative analyses of foraminiferal taxa were performed based on aliquots of 300 specimens (except for the samples where microfossils were extremely scarce) from the 64–250 μm fractions and separately from the fractions <64 μm in size. All the samples that were examined contained foraminiferal fossils. The majority of them yielded abundant and diversified assemblages that allowed biostratigraphic and ecological analyses. The taxonomy of the foraminifera follows Hanzliková (1972), Robaszynski et al. (1984), Caron (1985), Loeblich and Tappan (1988) and Holbourn et al. (2013). Ecological changes manifested by morphotypes, changes in specific and generic diversity, changes in size, and changes in relative abundance in the assemblages follow Murray (2006) and references therein. Selected planktonic and benthic foraminifera species from the Hyżne section are illustrated in Figures 3 and 4.

The microfacies and microfossils were additionally determined in eight thin sections. SEM images of microfossils and microfacies were taken using a scanning microscope and a stereoscopic microscope *Nikon SMZ 1500* with a digital camera *Nikon Coolpix-4500*. The samples and thin sections analysed are deposited at the Institute of Geological Sciences of the Jagiellonian University in Kraków.

A study of calcareous nannofossils has been conducted on 14 rock samples Hy1–Hy13. The samples were subjected to a standard treatment, i.e. each was thoroughly washed under running water and dried. From such prepared sample, a small amount of the precipitate was scraped on to a slide glass, which was ground into a thin filter after adding a few drops of water. The glass was thoroughly dried over a gas burner, and a drop of Canadian balm was added. Then, it was covered with a coverslip and dried in an oven. The smear slides prepared in this way were examined using a light microscope *Nikon Optiphot 2-pol* at x1500 magnification. Each slide was observed under cross-polarized light.

For the calcareous nannofossil zonation, the Cretaceous zonal scheme of Sissingh (CC, 1977) and Burnett (UC, 1998) and the Paleogene zonal scheme of Martini (NP, 1970) have been applied (Fig. 5). The state of preservation of the nannoplankton in the study samples was rated as good, i.e. the degree of recrystallization was so small that it allowed the determination of forms to the type and species. However, many forms have been significantly damaged mechanically. Selected calcareous nannoplankton species from the Hyżne section are illustrated in Figures 6 and 7.

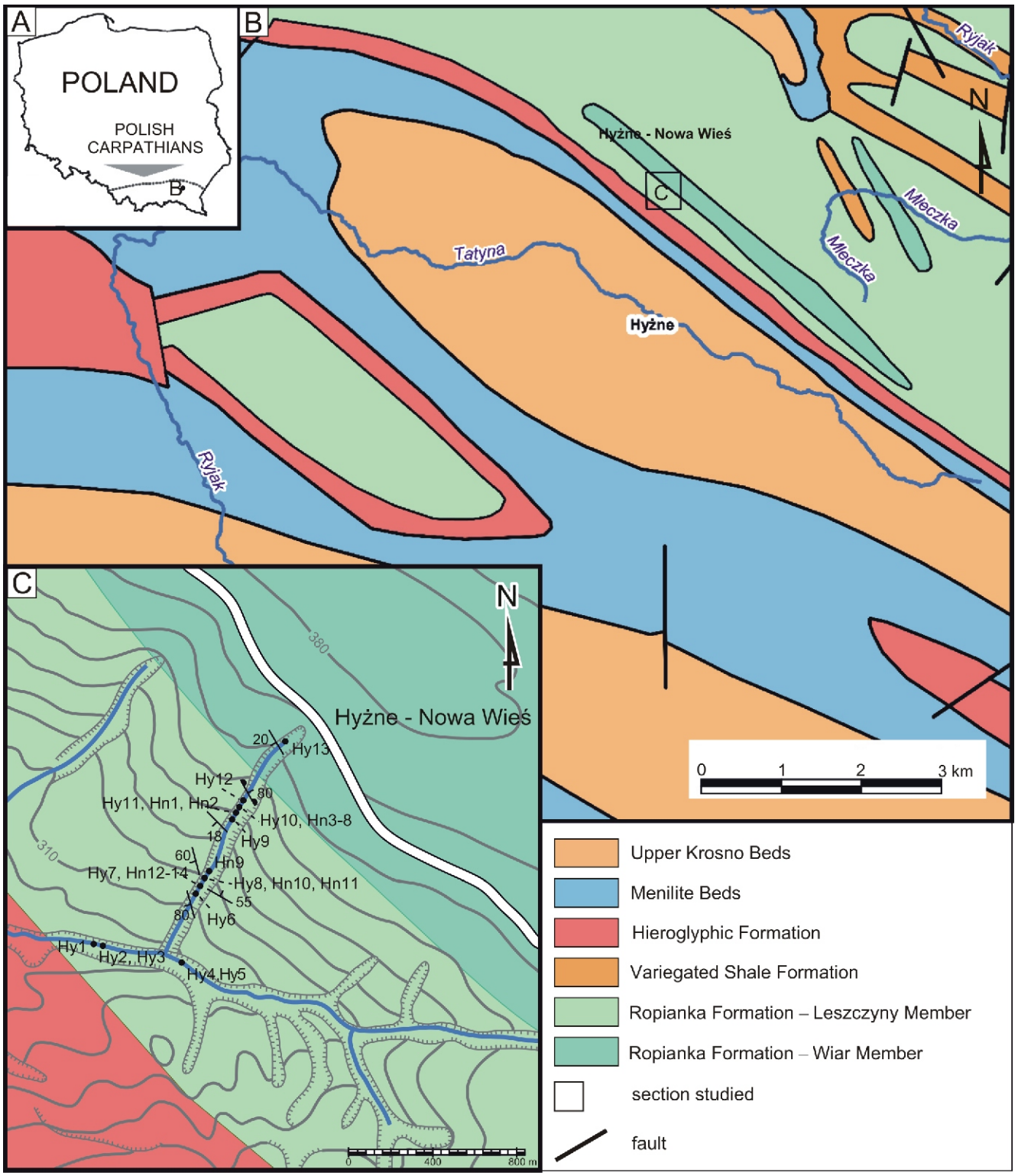


**Fig. 1. Location maps of Hyżne section**

**A** – location in Poland; **B** – location of studied section on the geological sketch-map of the Eastern Polish Carpathians (map based on Jankowski et al., 2004, simplified and modified); **C** – detailed geological map and location of samples Hy1–Hy13, Hn1–Hn14 (map based on Wdowiarz, 1949, modified)

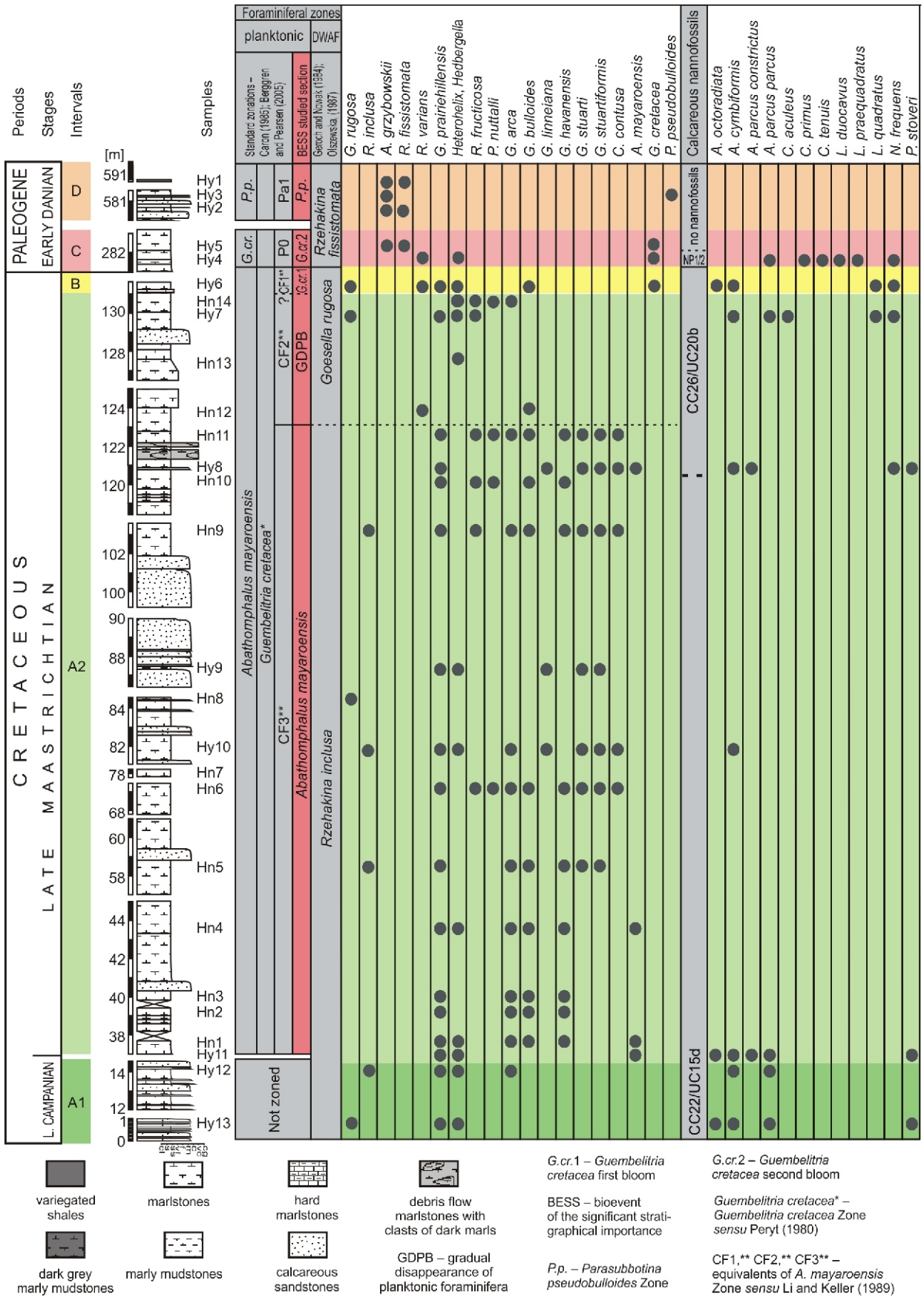


**Fig. 2. Detailed stratigraphic section with distribution of selected important foraminifera and nannofossils**

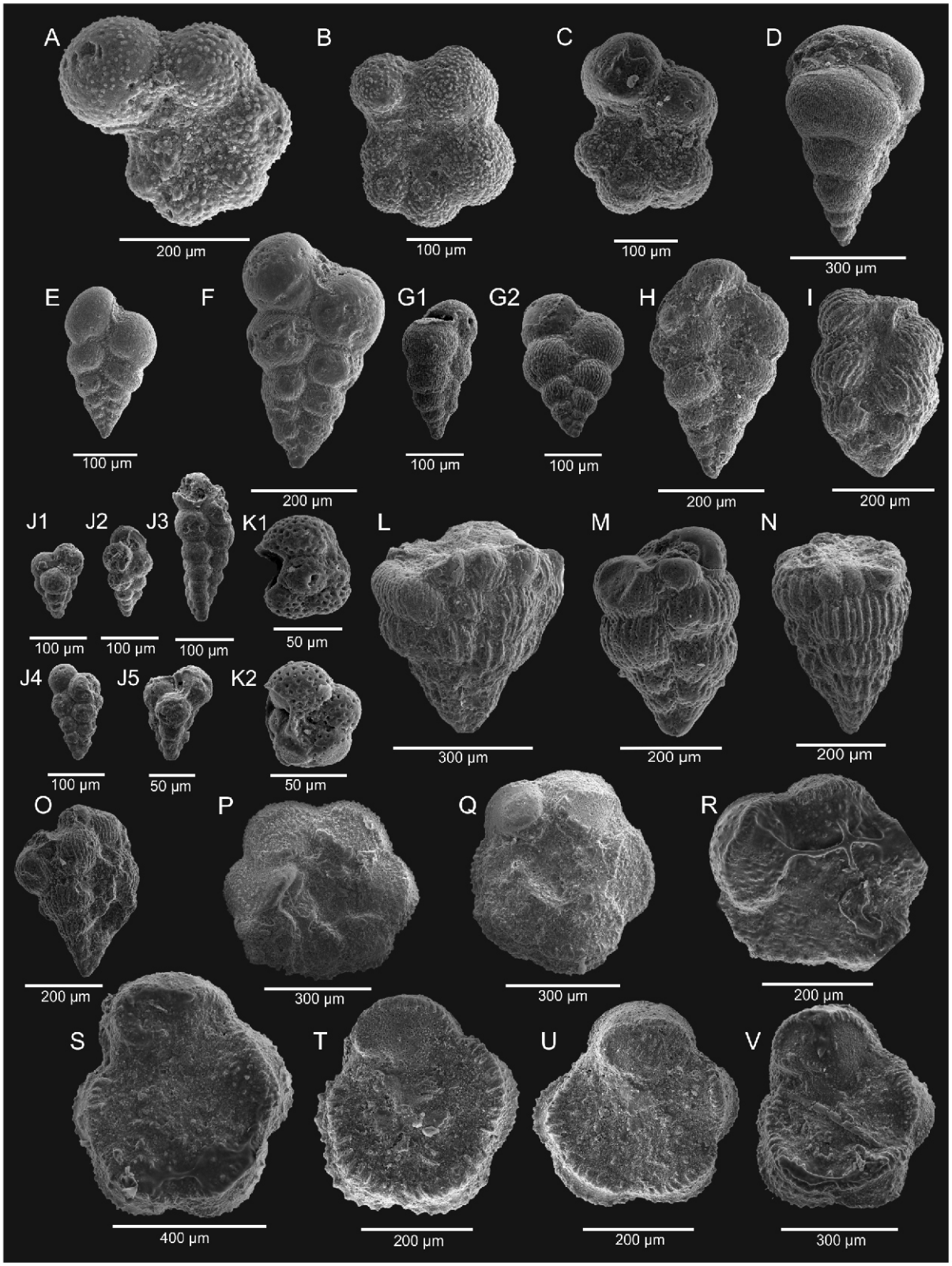


**Fig. 3. SEM images of selected planktonic foraminifera from the Hyżne section**

**A** – *Globigerinelloides prairiehillensis* Pessagno, sample Hn9; **B** – *Globigerinelloides prairiehillensis* Pessagno, sample Hn4; **C** – *Globigerinelloides prairiehillensis* Pessagno, sample Hn4; **D** – *Pseudotextularia nuttalli* (Voorwijk), sample Hn11; **E** – *Heterohelix navarroensis* Loeblich, sample Hy4; **F** – *Heterohelix navarroensis* Loeblich, sample Hy6; **G1** – *Heterohelix striata* Ehrenberg, sample Hy6; **G2** – *Heterohelix striata* Ehrenberg; sample Hy6; **H** – *Heterohelix planata* (Cushman), sample Hn9; **I** – *Heterohelix labellosa* Nederbragt, sample Hn9; **J1–J5** – *Guembelitria cretacea* Cushman; J1, J2; sample Hy6. J3, J4, sample Hy4. J5, sample Hy5; **K1–K2** – *Parasubbotina* cf. *pseudobulloides* (Plummer), sample Hy2; **L** – *Planoglobulina acervulinoides* (Egger), sample Hn9; **M** – *Pseudotextularia intermedia* De Klasz; sample Hy6; **N** – *Racemiguembelina fructicosa* (Egger), sample Hn9; **O** – *Planoglobulina acervulinoides* (Egger), sample Hy7; **P** – *Globotruncanita* cf. *stuartiformis* (Dalbiez), sample Hn4; **Q** – *Globotruncanita stuarti* (de Lapparent), sample Hn11; **R** – *Abathomphalus mayaroensis* (Bolli), sample Hn4; **S** – *Abathomphalus mayaroensis* (Bolli), sample Hy11; **T** – *Abathomphalus mayaroensis* (Bolli), sample Hy8; **U** – *Abathomphalus mayaroensis* (Bolli), sample Hy 9; **V** – *Abathomphalus mayaroensis* (Bolli), sample Hy9

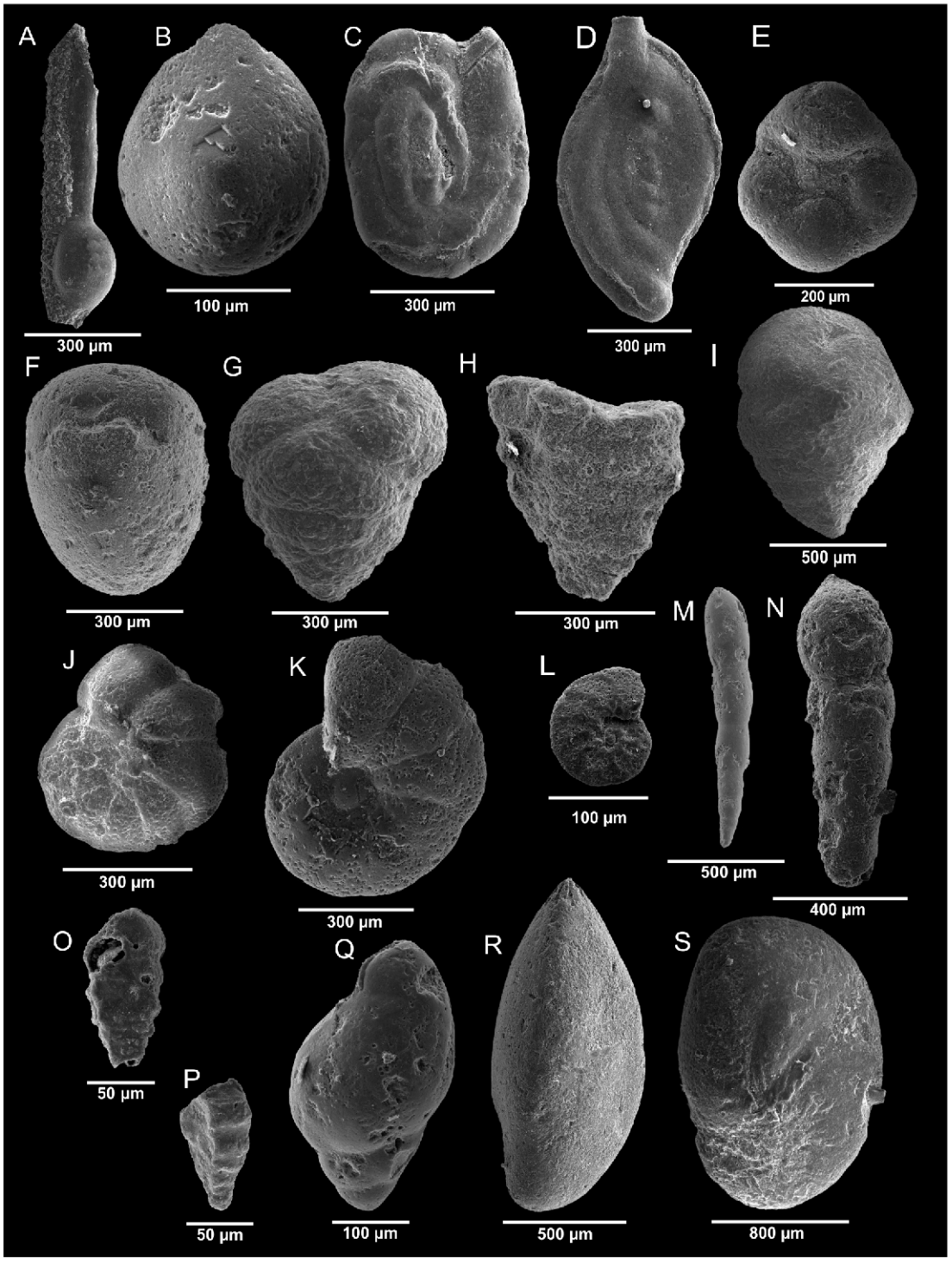


**Fig. 4. SEM images of selected benthic foraminifera from the Hyżne section**

**A** – *Ammolagena clavata* (Jones and Parker), sample Hy2; **B** – *Caudammina ovulum* (Grzybowski), sample Hy13; **C** – *Annectina grzybowskii* (Jurkiewicz), sample Hy5; **D** – *Rzehakina fissistomata* (Grzybowski), sample Hy7; **E** – *Quadrimorphina allomorphinoides* (Reuss), sample Hn9; **F** – *Goesella rugosa* (Hanzliková), sample Hy6; **G** – *Dorothia* sp., sample Hy3; **H** – *Marssonella* sp., sample Hy5; **I** – *Remesella* cf. *varians* (Glaessner), sample Hy12;**J** – *Brotzenella monterelensis* (Marie), sample Hy6; **K** – *Brotzenella monterelensis* (Marie), sample Hn12; **L** – *Brotzenella monterelensis* (Marie), sample Hy4; **M** – *Dentalina* sp., sample Hy4; **N** – *Nodosaria* sp., sample Hn10; **O** – *Bolivinita* sp., sample Hy4; **P** – *Bolivinita* sp., sample Hy4; **Q** – *Arenobulimina preslii* (Reuss), sample Hn10; **R** – *Marginulina* sp., sample Hy11; **S** – *Astacolus* sp., sample Hn5

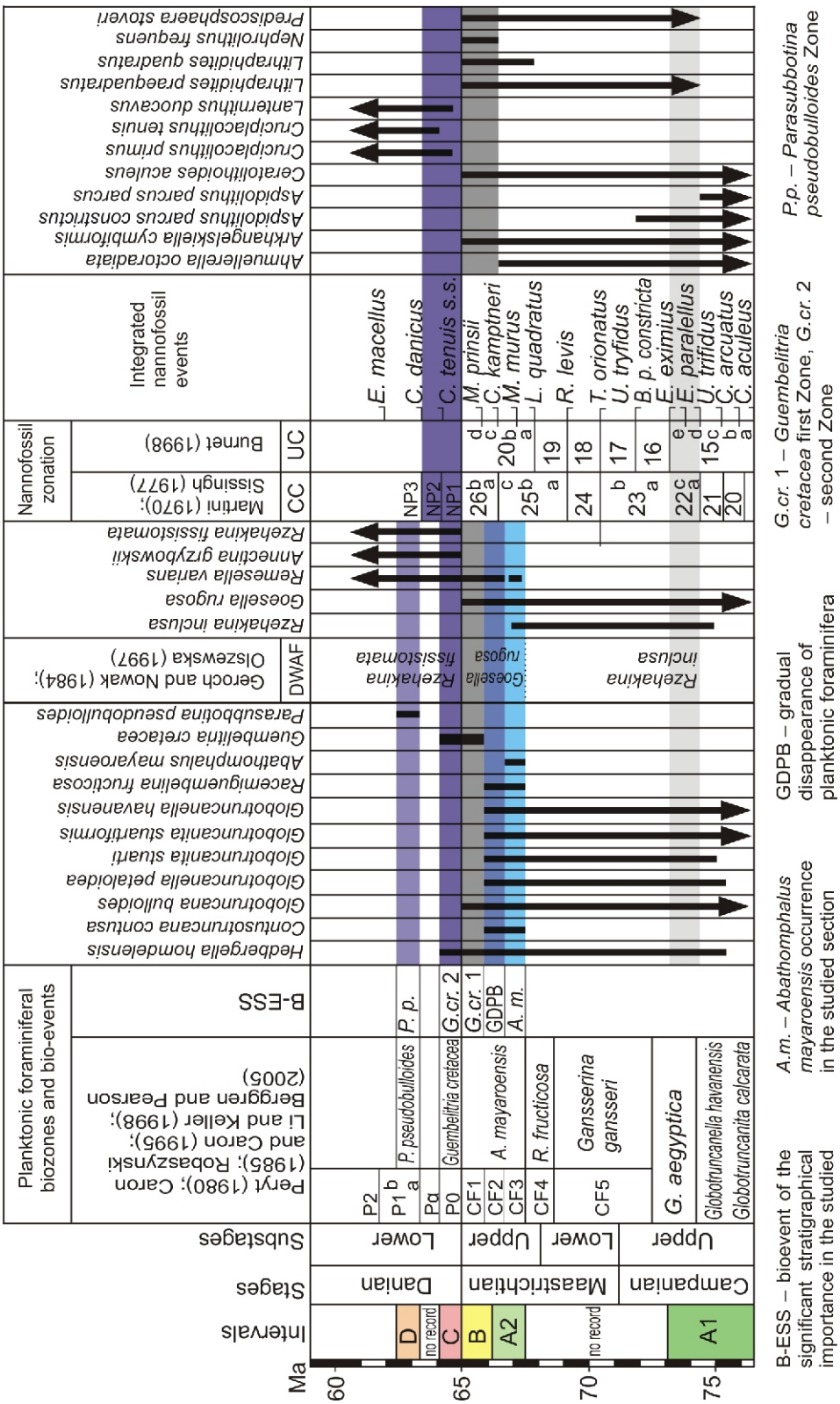


**Fig. 5. Correlation of foraminiferal zones of planktonic and agglutinated taxa and calcareous nannofossils against the chronostratigraphy in the studied section. Ranges of the foraminifera identified from the upper Campanian–Lower Paleogene rocks in the Hyżne section**

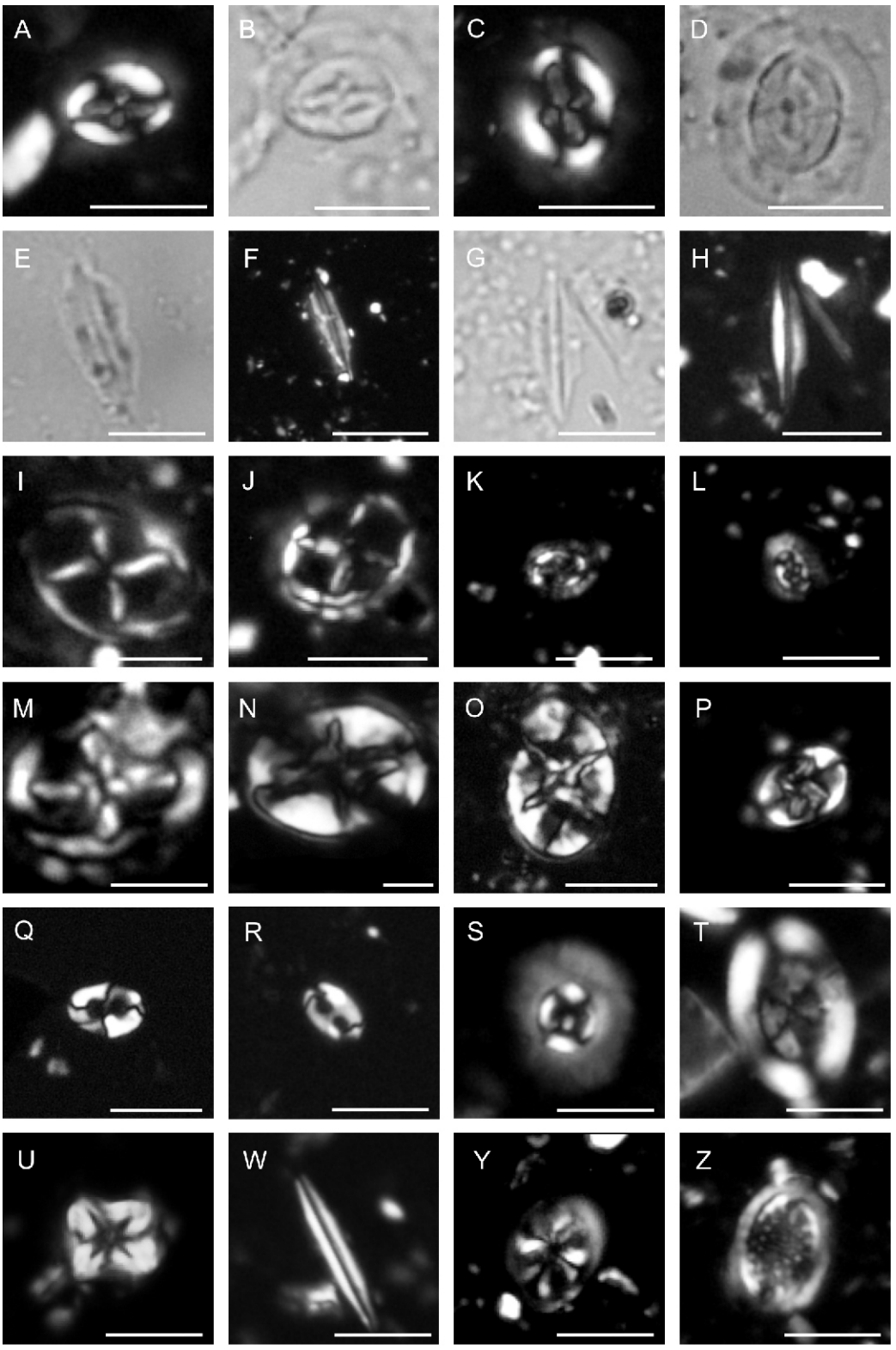


**Fig. 6. Calcareous nannoplankton from the Hyżne section**

**A, B** – *Cruciplacolithus primus* Perch-Nielsen, sample Hy4; **C, D** – *Cruciplacolithus tenuis* (Stradner) Hay and Mohler, sample Hy4; **E, F** – *Lithraphidites prequadratus* Roth, sample Hy6; **G, H** – *Lithraphidites quadratus* Bramlette and Martini, sample Hy6; **I** – *Chiastozygus litterarius* (Górka) Manivit, sample Hy13; **J** – *Prediscosphaera grandis* Perch-Nielsen, sample Hy11; **K** – *Prediscosphaera spinosa* (Bramlette and Martini) Gartner, sample Hy7; **L** – *Prediscosphaera stoveri* (Perch-Nielsen) Shafik and Stradner, sample Hy11; **M** – *Prediscosphaera arkhangelskyi* (Reinhardt) Perch-Nielsen, sample Hy11; **N** – *Eiffellithus turriseiffelii* (Deflandre) Reinhardt, sample Hy11; **O** – *Eiffellithus eximius* (Stover) Perch-Nielsen, sample Hy11; **P** – *Eiffellithus parallelus* Perch-Nielsen, sample Hy11; **Q, R** – *Lanternithus duocavus* Locker, sample Hy4; **S** – *Markalius inversus* (Deflandre) Bramlette and Martini, sample Hy6; **T** – *Aspidolithus parcus parcus* (Stradner) Noël, sample Hy13; **U** – *Micula staurophora* (Gardet) Stradner, sample Hy13; **W** – *Lithraphidites carniolensis* Deflandre, sample Hy13; **Y** – *Ahmuellerella octoradiata* (Górka) Reinhardt and Górka, sample Hy10; **Z** – *Cribrosphaerella ehrenbergii* (Arkhangelsky) Deflandre, sample Hy11; scale bars 5 μm

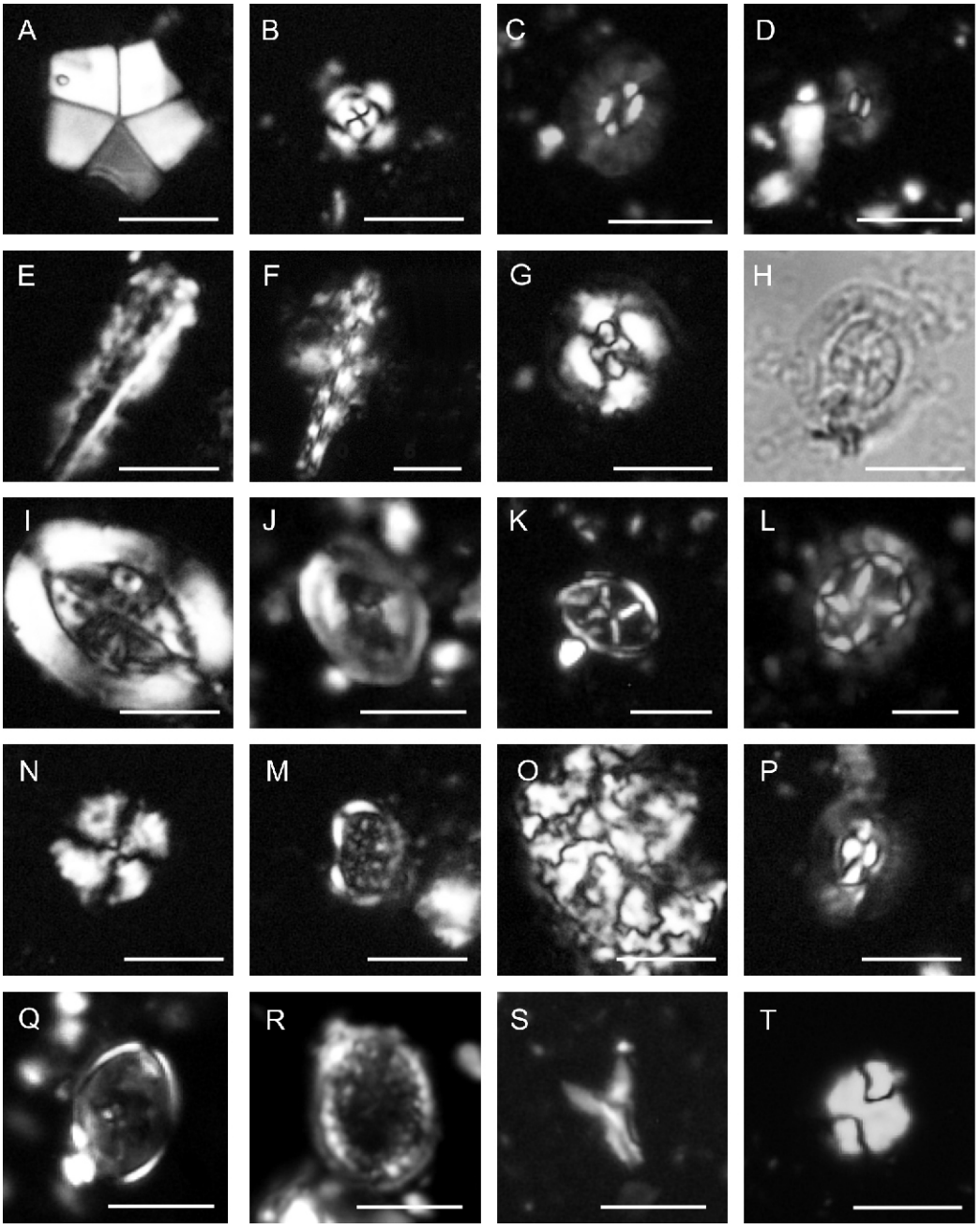


**Fig. 7. Calcareous nannoplankton from the Hyżne section**

**A** – *Braarudosphaera bigelowii* (Gran and Braarud) Deflandre, sample Hy4; **B** – *Cyclagelosphaera reinhardtii* (Perch-Nielsen) Romein, sample Hy4; **C** – *Biscutum magnum* Wind and Wise, sample Hy6; **D** – *Biscutum constans* (Górka) Black, sample Hy6; **E** – *Lucianorhabdus cayeuxii* Deflandre, sample Hy11; **F** – *Microrhabdulus decoratus* Deflandre, sample Hy11; **G, H** – *Cruciplacolithus tenuis* (Stradner) Hay and Mohler, sample Hy4; **I** – *Arkhangelskiella cymbiformis* Vekshina, sample Hy6; **J** – *Reinhardtites levis* Prins and Sissingh, sample Hy11; **K** – *Chiastozygus amphipons* (Bramlette and Martini) Gartner, sample Hy11; **L** – *Prediscosphaera cretacea* (Arkhangelsky) Gartner, sample Hy11; **M** – *Nephrolithus frequens* Górka, sample Hy6; **N** – *Watznaueria barnesae* (Black) Perch-Nielsen, sample Hy11; **O** – *Thoracosphaera* sp. Kamptner, sample Hy6; **P** – *Biscutum constans* (Górka) Black, sample Hy11; **Q** – *Calcicalathina oblongata* (Worsley) Thierstein, sample Hy11; **R** – *Angulofenestrellithus snyderi* Bukry, sample Hy13; **S** – *Ceratolithoides aculeus* (Stradner) Prins and Sissingh, sample Hy8; **T** – *Calculites obscurus* (Deflandre) Prins and Sissingh, sample Hy13; scale bars 5 μm

## RESULTS

### FORAMINIFERAL ASSEMBLAGES

Eighty-three taxa (species and genera), representing planktonic, calcareous benthic and agglutinated foraminifera and 74 calcareous nannoplankton species have been identified in the studied material (Figs. 2–7, Table 1, Appendix 1*). Based on changes in the composition of foraminiferal assemblages, such as variations in morphotypes, changes in specific and generic diversity, changes in the size, relative abundance, and the state of preservation, five intervals have been distinguished in the Hyżne section: A1, A2, B, C and D. They are characterized by the relative dominance of one of the major foraminiferal groups and each interval is characterized by a relevant foraminiferal assemblage.

### ASSEMBLAGES OF INTERVALS A1 AND A2

The diversity, abundance and preservation of foraminiferal tests vary in the studied assemblages that include planktonic foraminifera both large, ornamented, complex morphotypes with single-keeled and double-keeled taxa, and small, simple non-keeled taxa.

In the assemblage of interval A1 (samples Hy13–Hy12, Fig. 2), *Globotruncana arca*, *G.* sp., *Globigerinelloides prairiehillensis* and *Heterohelix* sp. are present.

The calcareous benthic taxa are poorly preserved and represented mostly by small forms of single calcareous benthic taxa, including *Eponides* sp., *Osangularia* sp. and *Dentalina* sp. Agglutinated taxa are common and better preserved. They include *Ammodiscus* sp., *Caudammina*, *Karrerulina*, *Recurvoides*, *Ammosphaeroidina pseudopauciloculata*, *Dorothia crassa*, *Kalamopsis grzybowskii*, *Conglophragmium* sp. and *Rzehakina* sp.

The assemblage of interval A2 (samples Hy11–Hn14, Fig. 2) contains more diverse planktonic foraminifera, including *G. arca*, *G. bulloides*, *G. linneiana, G. petaloidea, Globotruncanita stuarti*, *Gl. stuartiformis, Globotruncanella petaloidea*, *Contusotruncana contusa*, *Abathomphalus mayaroensis*, *Hedbergella holmdelensis*, *H. monmouthensis*, *Heterohelix globulosa*, *H. moremani, H. navarroensis*, *H. striata*, *Globigerinelloides prairiehillensis*, *Pseudotextularia nuttalli*, *Pseudotextularia elegans*, *Racemiguembelina fructicosa*, *Planoglobulina acervulinoides*, *Rugoglobigerina rugosa*, and *Archaeoglobigerina blowi* (Fig. 3).

In the lower part of interval A2, the foraminifera are most diversified taxonomically. Their preservation varies from well (partially filled or empty tests) to poorly preserved, and their abundance ranges from numerous to rare, depending on the sample. In the upper part of the interval, many tests especially planktonic foraminifera show traces of dissolution (Hy8).

Benthic calcareous foraminifera are represented by the most abundant specimens of *Cibicidoides* and *Gyroidinoides*, as well as by *Gavelinella*, *Osangularia, Flabellina, Dentalina, Nodosaria, Pleurostomella, Frondicularia, Marginulina*, *Quadrimorphina, Allomorphina, Glandulina, Astacolus* (Fig. 4N, R, S). Agglutinated foraminifera are relatively rare (except for sample Hy11). They are represented by *Rhabdammina*, *Nothia, Ammodiscus cretaceus*, *Glomospira, Caudammina ovula*, *Conglophragmium, Rzehakina inclusa*, *Recurvoides*, *Trochamminoides, Saccammina* and some taxa of calcareous-cemented agglutinated forms, such as *Gaudryina*, *Tritaxia*, *Arenobulimina*, *Dorothia*, *Goesella rugosa* and *Arenobulimina preslii* (Fig. 4).

This interval is characterized by calcareous nannoplankton species such as: *Aspidolithus parcus constrictus, A. parcus parcus, Ahmuellerella octoradiata, Arkhangelskiella cymbiformis, Biscutum constans, B. magnum, Calcicalathina oblongata, Calculites obscurus, Ceratolithoides aculeus, Chiastozygus amphipons, Cretarhabdus crenulatus, Cribrosphaerella ehrenbergii, Cyclagelosphaera deflandrei, C. reinhardtii, Discorhabdus ignotus, Eiffellithus turriseiffelii, Eprolithus moratus, Gartnerago segmentatum, Kamptnerius magnificus, Lithraphidites bolii, Lucianorhabdus cayeuxii, Markalius inversus, Micula concava, Microrhabdulus decoratus, Okkolithus australis, Prediscosphaera arkhangelskyi, P. cretacea, P. honjoi, P.* cf. *grandis* (fragment), *P. ponticula, P. stoveri, P. spinosa, Reinhardtites anthoporus, R. levis, Rhagodiscus angustus, Staurolithites imbricatus, Tranolithus* cf. *phacelosus, Thoracosphaera* sp., *Watznaueria barnesae, W. biporta, Zeugrhabdotus noeliae* (Figs. 6 and 7).

Additionally, fragments of inoceramid shells and spines of echinoderms are present.

### ASSEMBLAGE OF INTERVAL B

Stratigraphically higher in the section, the assemblage of the interval B was distinguished in sample Hy6 (Fig. 2). It is characterized by a decrease in diversity in comparison with the assemblage from interval A2. It contains mainly simple small, non-keeled, thin-walled *Guembelitria cretacea* and thin-walled, biserial heterohelicids (*Heterohelix* div. sp.). The keeled and non-keeled trochospiral forms of planktonic foraminifera are exceptionally rare and represented by single forms of *Globotruncana bulloides* and *Rugoglobigerina rugosa*. The finest fraction (<64 μm) contains biserial, small, heterohelicids and a high number of *G. cretacea* (Fig. 3). Generally, the foraminiferal tests are poorly preserved and many of them show traces of dissolution. The planktonic foraminifera from interval B are smaller in comparison to planktonic foraminifera from intervals A1 and A2. Benthic agglutinated forms are present, although specimens of agglutinated with calcareous cement *Goesella rugosa, Remesella varians* and *Arenobulimina preslii* are very scarce.

The assemblage of calcareous nannoplankton include: *Ahmuellerella octoradiata, Arkhangelskiella cymbiformis, Biscutum constans, B. magnum, Calculites obscurus, Cribrosphaerella ehrenbergii, Cyclagelosphaera deflandrei, C. reinhardtii, Eiffellithus gorkae, E. turriseiffelii, E. paralellus, Lithraphidites quadratus, Markalius inversus, Micula decussata, Nephrolithus frequens, Orastrum colligatum, Prediscosphaera arkhangelskyi, P. cretacea, P. spinosa, R. surirella, Tranolithus phacelosus, Zeugrhabdotus diplogrammus* (Figs. 6 and 7).

### ASSEMBLAGE OF INTERVAL C

The assemblage of interval C (samples Hy4, Hy5, from the dark grey marly mudstones) displays the most important changes in relation to previous assemblages. Among them, the most characteristic feature is the size reduction of planktonic and calcareous benthic foraminifera. They are smaller in comparison with forms from intervals A1, A2 and B (Fig. 4J–L). The dominance of small-sized *Heterohelix* sp. and *Guembelitria*

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1536

Table 1

**Age and synchronicity of planktonic and benthic foraminiferal and calcareous nannoplankton bioevents across the Cretaceous–Paleogene boundary interval (Late Cretaceous–Early Paleogene)**

| Period | Stages | Intervals of foraminiferal assemblages | BESS in the studied section | Zones: Planktonic foraminifera | Zones: Agglutinaed foraminifera | Zones: Calcareous nannoplankton | Number of sample | Events | | Primary environmental conditions | Primary bathymetry |
|---|---|---|---|---|---|---|---|---|---|---|---|
| PALEOGENE | EARLY DANIAN | D | *P. pseudobulloides* | *P.cf. pseudobulloides* | *Rzehakina fissistomata* | barren | Hy3-Hy1 | • glass spherules<br>• dominance of deep water agglutinated foraminifera DWAF<br>• occurrence of agglutinated foraminifera with calcareous cement<br>• low diversity of foraminifera<br>• *Parasubbotina* cf. *pseudobulloides*<br>• single forms of planktonic foraminifera | lo | optimal | (3) middle–lower bathyal, above local CCD, below local FL |
| | | | Pα | no record | | | | | | | |
| | | C | *Guembelitria cretacea* 2 | *Guembelitria cretacea* | *Rzehakina fissistomata* | NP1/2 | Hy5, Hy4 | • *Cruciplacolithus tenuis*<br>• *Cruciplacolithus primus*<br>• *Lanternithus duocavus*<br>• *Rzehakina fissistomata*<br>• *Anectina grzybowskii*<br>• size reduction (Lilliput effect)<br>• extinction the large Heterohelicidae<br>• bloom of *Bolivinita* sp.<br>• second bloom of *Guembelitria cretacea*<br>• low diversity of foraminifera<br>• glauconitic grains<br>• glass spherules<br>• dark-grey marly mudstones layer | FO<br>FO<br>FO<br>lo<br>lo | stressed, with tendency to more stable | (2) shelf margin |
| CRETACEOUS | LATE MAASTRICHTIAN | B | (3)*Guembelitria cretacea* 1 | *Abathomphalus mayaroensis* | *Goesella rugosa* | CC26, UC20B | Hy6 | • *Lithraphidites quadratus*<br>• *Nephrolithus frequens.*<br>• *Remessella varians*<br>• *Goessella rugosa*<br>• appearance of opportunistic *Bolivinita*<br>• dominance (first bloom) of the opportunistic *Guembelitria cretacea* | FO<br>FO<br>ho<br>lo | stressed | (2) shelf margin |
| | | | (2) GDPBF | | | No zoned | Hn11–Hn14 | • *Racemiguembelina fructicosa*<br>• *Contusotruncana contusa*<br>• *Guembelitria cretacea*<br>• moderate foraminiferal size fluctuations (size reduction)<br>• gradual extinction of the large K-strategy, specialized foraminifera (the mass extinction event)<br>• dissolution of tests of planktonic foraminifera<br>• low diversity of foraminifera<br>• glauconitic grains | ho<br>ho<br>lo<br>lo | | |
| | | A2 | (1) *A. mayaroensis* | | *Rzehakina inclusa* | No zoned | Hy11–Hy8 | • dissolution of tests of planktonic foraminifera<br>• *Abathomphalus mayaroensis*<br>• planktonic foraminifera have grown to the large sizes<br>• high diversity of planktonic foraminifera K- and r-strategy<br>• appearance of K-strategy foraminifera<br>• *Abathomphalus mayaroensis* | ho<br>lo | optimal | (1) upper bathyal, above local FL |
| | | | | *no record* | | | | | | | |
| | CAMPANIAN | A1 | | No zoned | *Rzehakina inclusa* | C22, UC15d | Hy13, Hy12 | • *Rzehakina inclusa*<br>• *Globotruncanella petaloidea*<br>• dominance of r-strategy foraminifera<br>• high diversity planktonic and benthic foraminifera | lo<br>lo | optimal | (1) upper bathyal, above local FL |

DWAF – deep-water agglutinated foraminifera; CCD – carbonate compensation depth; FL – foraminiferal lysocline (Kennett, 1982); OCF – organic carbon flux; FO – first occurrence; lo – lowest occurrence observed in the section; ho – highest occurrence observed in the section; BESS – bioevents of significant stratigraphical importance: (1) *A. mayaroensis–Abathomphalus mayaroensis* occurrence in the section, (2) GDPBF – gradual disappearance of planktonic bathypelagic foraminifera, (3) *Guembelitria cretacea* 1 – *Guembelitria cretacea* first bloom Zone *sensu* Peryt, 1980, *Guembelitria cretacea* 2 – *Guembelitria cretacea* second bloom Zone *sensu* Pardo et al. (1996)

*cretacea* in the fine fractions (<64 μm) is observed. Tests of *Globigerinelloides* sp., and single trochospiral taxa of *Rugoglobigerina* with globular, ornamented chambers, occur sporadically. Keeled, large foraminiferal planktonic species are absent.

The benthic foraminifera of interval C contain both the calcareous and agglutinated, epifaunal and infaunal forms (Fig. 4). The most abundant taxa are the calcareous *Brotzenella monterelensis* (Fig. 4J–L), *Cibicides* sp., *Osangularia* sp., *Globoquadrina* sp., and *Planulina* sp. Additionally, a single specimen of *Nodosaria* sp. is present in the 64–150 μm fraction, along with the dominance (up to 50%) of *Bolivinita* sp. (Fig. 4) in the smallest (<64 μm) fraction.

The agglutinated foraminifera of interval C are dominated by tubular opportunistic forms, such as: *Bathysiphon* sp., *Nothia excelsa* and *Rhabdammina cylindrica* and *Ammolagena clavata* (sample Hy5). Single tests of *Glomospira charoides*, relatively abundant *Rzehakina fissistomata* and *Annectina grzybowskii,* and comparatively rare *R. epigona* are present. They co-occur with glauconite grains and glass spherules.

The interval C is characterized by the presence of many redeposited Cretaceous species of calcareous nannoplankton such as: *Aspidolithus parcus parcus, Braarudosphaera* sp., *B. bigelowii, Calculites obscurus, Cyclagelosphaera reinhardtii, Lithraphidites prequadratus, Micula concava, M. staurophora, Nephrolithus frequens, Watznaueria barnesae, Zeugrhabdotus sigmoides.* Some early Danian species, such as *Cruciplacolithus primus, C. tenuis* and *Lanternithus duocavus* are also present (Figs. 6 and 7).

### ASSEMBLAGE OF INTERVAL D

In the assemblage of interval D (samples Hy2, Hy3, Hy1), the planktonic foraminifera are absent, except for single, poorly preserved specimens of *Parasubbotina* cf. *pseudobulloides* (in sample Hy2) with poorly visible features of chambers and apertures, which cause difficulties in taxonomic identification. The benthic foraminifera are dominated by agglutinated taxa with organically cemented walls, such as *Ammodiscus* sp., *Annectina grzybowskii*, *Caudammina ovulum*, *Glomospira* div. sp., *Nothia* sp., *Rhabdammina* sp., *Recurvoides* spp., *R. fissistomata*, *Trochammina* sp., *Trochamminoides* sp. and *Saccammina* sp., and with an exceptionally large contribution of *Ammolagena clavata*. Moreover, a few agglutinated with calcareous cement *Dorothia beloides* and *Gaudryina pyramidata,* and single representatives of the benthic calcareous genera *Gyroidinoides* and *Cibicidoides* are present. In this interval, there is lack of calcareous nannoplankton.

## INTERPRETATION AND DISCUSSION

### FORAMINIFERAL BIOSTRATIGRAPHY

The foraminiferal assemblages consist of diverse associations of planktonic and benthic foraminifera, among which several taxa are typical of the Late Cretaceous and Early Paleogene. For biostratigraphic considerations, the standard planktonic foraminiferal zonations proposed by Caron (1985), Robaszyński and Caron (1995), Premoli-Silva et al. (2003), Premoli-Silva and Verga (2004), Berggren and Pearson (2005), and Ogg et al. (2016) are used. For benthic agglutinated foraminifera, the zonations by Geroch and Nowak (1984) and Olszewska (1997) are followed.

In the lowest part of the Hyżne section, the assemblage of interval A1 (Fig. 3) is dominated by *Heterohelix* spp. and *Hedbergella* spp. No index planktonic foraminiferal species have been recognized, except for *Globotruncanella petaloidea* that may indicate an earliest Campanian–latest Maastrichtian time interval. A similar assemblage was described from the upper Campanian to lower Maastrichtian deposits of the Subsilesian Nappe (Machaniec, 2000; Machaniec et al., 2000, 2001, 2005; Leśniak and Machaniec, 2001; Machaniec and Zapałowicz-Bilan, 2005). The agglutinated species *Rzehakina inclusa* (Fig. 5) is characteristic of the Upper Cretaceous to the Lower Paleogene in the Alpine-Carpathian region of Southern and Central Europe (Geroch and Nowak, 1984). In the Polish Carpathians, Morgiel and Olszewska (1981) recognized the *R. inclusa* assemblage of Campanian–Maastrichtian age, based on the maximum occurrence of this species. Olszewska (1997) described the *R. inclusa* Zone as late Campanian to Maastrichtian in age and defined it as the interval zone from the lowest occurrence of the nominate taxon to the lowest occurrence of *Rzehakina fissistomata.*

The first planktonic foraminiferal zone has been distinguished in the foraminiferal assemblage of interval A2. It is *Abathomphalus mayaroensis* Zone *sensu* Caron (1985), which was defined by the total range of *A. mayaroensis* and dates the late Maastrichtian in the Tethyan realm (Fig. 5). In the studied section, the samples above the highest occurrence of *A. mayaroensis* contain only a single specimen of keeled planktonic Cretaceous foraminifera, i.e. *Globotruncana arca*. The disappearance of Cretaceous keeled planktonic foraminifera is inconsistent with the definition of the upper boundary of the *A. mayaroensis* Zone (Caron, 1985; Premoli-Silva and Verga, 2004). The *A. mayaroensis* Zone, according to Caron (1985), should extend up to the K-Pg boundary, especially in the low geographical latitudes. However, *A. mayaroensis* is usually a rare species, even at low latitudes for which it is typical (Molina et al., 2006; Keller and Abramovich, 2009), or it can be even absent therein (Speijer and van der Zwaan, 1996; Tshakreen et al., 2017).

The Outer Carpathian basins and the studied section were located in the middle latitudes, in which *A. mayaroensis* occurred relatively widely and its first appearance is dated to the earliest late Maastrichtian. This species continues until the Maastrichtian–Paleogene boundary, e.g., in the Subsilesian Nappe (Gasiński et al., 2001; Machaniec, 2002; Tshakreen and Gasiński, 2004), and in the Eastern Carpathians (Ţabără et al., 2017). However, disappearance of the index species *A. mayaroensis* before the mass extinction at the K-Pg boundary has been recorded in the studied section (Table 1). A similar trend was observed by Kędzierski et al. (2015) in the Ropianka Formation of the Skole Nappe.

The assemblage above the highest occurrence of *A. mayaroensis* (sample Hy8; Figs. 2 and 5) and below the highest occurrence of *Contusotruncana contusa* and *Racemiguembelina fructicosa* (sample Hn14; Figs. 2 and 5) is characterized by gradual disappearance of the ornamented, large planktonic, keeled forms such as *Abathomphalus, Contusotruncana*, *Globotruncanita* and *Globotruncanella*, as well as ornamented, large, specialized Heterohelicidae e.g. *Racemiguembelina, Planoglobulina, Pseudotextularia*. This change is possibly coeval with the planktonic foraminiferal CF2 Zone (*sensu* Li and Keller, 1998), whose top is determined by the last occurrence (LO) of *Gansserina gansseri* in the late Maastrichtian.

Another stratigraphically important bioevent in the assemblage of interval A2 (sample Hy12) is the lowest occurrence of the calcareous-cemented agglutinated species *Remesella varians.* For the first time *R. varians* was described from the uppermost Cretaceous to Paleocene in the NW Caucasus

(Glaessner, 1937). This species was also reported from Maastrichtian–Paleocene deposits of the North Atlantic (e.g., Kuhnt et al., 1989) and Western Tethys (Kaminski and Gradstein, 2005), and from the middle–upper Maastrichtian (Malata et al., 1996; Bąk, 2004) and Paleocene deposits of the Northern Tethys (Baliniak, 2018).

The younger assemblage of the next interval B (sample Hy6) is characterized by a very high number of *Heterohelix* spp., *Globigerinelloides* spp. and a bloom of the very small specimens of *Guembelitria cretacea* (Fig. 3 and Table 1) in the fine fraction (<64 μm) found for the first time in the Outer Carpathians. *Guembelitria cretacea* was identified in the upper Maastrichtian of the Middle Vistula River Valley in Poland. Due to the lack of *Abathomphalus mayaroensis* in that area, the index species was replaced by *G. cretacea* (Peryt, 1980). Thus, the *G. cretacea* Zone *sensu* Peryt is the equivalent of the planktonic foraminiferal *A. mayaroensis* Zone (Caron, 1985), characteristic of shallow, high latitude marginal basins (Peryt, 1980 and references cited therein). The co-occurrence of *G. cretacea* and representatives of *Heterohelix* spp. and *Globigerinelloides* spp. are also characteristic of the south-eastern margin of Tethys (Israel, Egypt, India), where the characteristic extinction of keeled forms started below the K-Pg boundary (Mukhopadhyay, 2012, 2016; Keller et al., 2016; Punekar et al., 2016; Keller et al., 2018 and references cited therein). Non-keeled planktonic foraminifera are very abundant and relatively diverse in the interval studied, which is typical of the Maastrichtian (Hart, 1999).

The assemblage of interval B also contains calcareous-cemented agglutinated species *Goesella rugosa.* According to Geroch and Nowak (1984), the LO of *G. rugosa* indicates the late Maastrichtian. These authors argued that, the LO of *G. rugosa* coincides in the Polish Outer Carpathians with the K-Pg boundary and with the base of the lowest occurrence of *Rzehakina fissistomata*. This concept is in full agreement with observations from northern Spain (Kuhnt and Kaminski, 1997). The co-occurrence of *R. varians* and *G. rugosa* is restricted to the late Maastrichtian (Kuhnt and Kaminski, 1997).

Another significant increase in the abundance of planktonic *Guembelitria cretacea* is observed in the assemblage of interval C and has been considered as the second bloom of this species. The *G. cretacea* Zone is an acme zone characterized by abundant occurrence of the Maastrichtian survivor species. The second bloom of this species is observed after the K-Pg transition event (e.g., Smit and Romein, 1985; Gallala and Zaghbib-Turki, 2010). The *G. cretacea* second bloom Zone indicates the lowermost Paleocene interval, called the P0 Zone (e.g., Berggren et al., 1995; Ogg and Hinnov, 2012). In the studied section, the acme *G. cretacea* Zone has been distinguished for the first time in the Outer Carpathians. So far, none of these blooms was observed in the other turbiditic series of the Polish Carpathians, but it has been distinguished at the Lechówka section in the Lublin Upland, E Poland, in the far Carpathian foreland (Machalski et al., 2016).

Finally, in the Hyżne section, the standard *Abathomphalus mayaroensis* Zone *sensu* Caron (1985) comprises, in a stratigraphic order: (1) interval with *A. mayaroensis* occurrence, (2) interval with a gradual disappearance of keeled taxa, and (3) interval with the *G. cretacea* first bloom. It seems that these bio-events have a great stratigraphic significance, especially in the sections where there is lack of *A. mayaroensis* occurrence. The latest Maastrichtian to the earliest Paleocene marine sediments contain *G. cretacea* as an important component, which is used to recognize the K-Pg transition as a survivor taxon across the boundary (Hofker, 1978; Smit, 1982; Canudo et al., 1991; Liu and Olsson, 1992; Abramovich et al., 2002, 2010; Keller, 2002, 2004; Coccioni and Luciani, 2006; Keller et al., 2016). The *Guembelitria cretacea* Zone was defined for the first time as the interval ranging from the K-Pg boundary to the FOs of Paleogene species (Smit, 1982). It was modified by Keller (1988) into subdivisions including the P0a – *G. cretacea* subzone, then was revised as the P0 Zone from the mass extinction of Maastrichtian species to the LO of *Parvularugoglobigerina eugubina* (Keller et al., 1995). D'Hondt and Keller (1991) and Pardo et al. (1996) defined the P0 Zone as the partial range of *G. cretacea* following the extinction of large globotruncaniids and preceding the FO of *P. eugubina*.

According to Geroch and Nowak (1984) the FO of *Rzehakina fissistomata* is in the early Paleocene. In the Hyżne section, it was observed in the P0 Zone. This species is known in the Polish Outer Carpathians from the Paleocene (Morgiel and Olszewska, 1981; Geroch and Koszarski, 1988; Olszewska, 1997; Oszczypko et al., 2005; Waśkowska-Oliwa, 2008, and papers cited therein). However, the lowest appearances of *R. fissistomata* seem to be diachronous. Its lowest occurrence is recorded in the uppermost Maastrichtian of the Skole Unit, Outer Carpathians, Poland (Kędzierski et al., 2015). Therefore, the Paleocene age is not assigned to the first occurrence of *R. fissistomata* in the northern Tethys. Nevertheless, the lowest occurrence of the *R. fissistomata* bioevent is approximately related to the K-Pg transition. Another very characteristic agglutinated species of this zone, *Annectina grzybowskii*, as an equivalent of the index taxon in the case of absence of *R. fissistomata* (Geroch and Nowak, 1984), is observed in the Hyżne section.

In interval D (Hy1, Hy3, Hy2), the index taxon *Parasubbotina* cf. *pseudobulloides* (Fig. 3, K1, K2) indicates the P1a Zone in the upper part of the Early Paleocene. The foraminiferal assemblages contain also a few calcareous benthic foraminifera and the calcareous-cemented agglutinated forms. of *Dorothia crassa*. However, the youngest foraminiferal association from the top of the succession contains mainly typical deep-water agglutinated foraminifera with organic cement (DWAF), such as *Ammodiscus* sp., *Caudammina* sp., *Hormosina* sp., *Recurvoides* sp., *Rzehakina* sp., *Caudammina excelsa*, *Caudammina* cf. *ovula,* and *Hormosina velascoensis.*

## CALCAREOUS NANNOPLANKTON BIOSTRATIGRAPHY

Samples Hy13–Hy10 are assigned either to the CC 22 Zone (upper Campanian) or UC15e due to lack of marker taxa that would allow discrimination between them. The assignation to the zones is based on the first appearance of the youngest taxon.

Samples Hy8–Hy6 were included either in the late Maastrichtian CC 26 Zone (Sissingh, 1977) or in the UC 20b Zone (Burnett, 1998) due to the occurrence of *Lithraphidites quadratus* and *Nephrolithus frequens*. There are no younger forms in these samples, such as *Micula prinsii*, which appear in the uppermost part of the CC 26 Zone.

The nannoplankton assemblage from sample Hy4 is dominated by redeposited Late Cretaceous forms, such as *Aspidolithus parcus parcus*, *Braarudosphaera* sp., *Braarudosphaera bigelowii, Calculites obscurus, Cyclagelosphaera reinhardtii, Lithraphidites prequadratus*, *Micula concava, Micula staurophora, Nephrolithus frequens, Watznaueria barnesae* and *Zeugrhabdotus sigmoides.* The presence of *Cruciplacolithus tenuis*, *Cruciplacolithus primus* and *Lanternithus duocavus* (Figs. 6 and 7) allows ascription of sample Hy4 to the NP1 *Markalius inversus* Zone (lower Danian). According to Martini (1970), the NP1 Zone is defined by LO of Cretaceous coccoliths to FO of *Cruciplacolithus tenuis*.

In the studied calcareous nannoplankton assemblages, the uppermost part of the CC 26 Zone has not been determined due to the lack of *Micula prinsii* Perch-Nielsen. In earlier studies (Jugowiec-Nazarkiewicz, 2007), *M. prinsii* was recorded in the Węglówka Marl (Bezmiechowa), Rybie Sandstone and Frydek Marl-like deposits in the Pluskawka stream section of the Subsilesian Nappe. *M. prinsii* was found in the top part of the *A. mayaroensis* Zone in the Gaj section of the Skole Nappe (Kędzierski et al., 2015).

According to Perch-Nielsen et al. (1982), Berggren and Pearson (2005) and Molina et al. (2006), a complete K-Pg section should contain, from the bottom upwards, the latest Maastrichtian nannofossil *Micula prinsii* Zone, early Danian planktonic foraminifera *Guembelitria cretacea* Zone (P0, including the K-Pg boundary clay), and *Parvularugoglobigerina eugubina* Zone (P1 ). However, immediately above the K-Pg boundary, an interval with sparse nannofossils is present in most sections. Therefore, the relatively low resolution of biozones does not exclude possible hiatuses in sections considered so far to be biostratigraphically complete (MacLeod and Keller, 1991). In the studied samples, the Paleocene assemblage is dominated by redeposited Cretaceous taxa. *Thoracosphaera* sp. is very rare and *Braarudosphaera* is represented by a few specimens in sample Hy4. However, the presence of *Cruciplacolithus tenuis, Cruciplacolithus primus* and *Lanternithus duocavus* allows including sample Hy4 to the NP1/2 Zone (early Danian).

In the Hyżne section, the K-Pg boundary is placed between the foraminiferal zones of *Abathomphalus mayaroensis* (lower late Maastrichtian) and *Guembelitria cretacea* (earliest Paleocene), and between the calcareous nannoplankton zones of CC26 and NP1/2 (Fig. 5).

## PALAEOECOLOGY

Composition of the foraminiferal assemblages, their quantitative analysis in the Hyżne section and interpretations of relevant environmental conditions are presented in Figure 8. The planktonic/benthic (P/B) foraminifera ratio (= planktonic/planktonic + benthic) is regarded to be an indicator of palaeobathymetry and palaeoproductivity (e.g., Berggren and Diester-Haass, 1988; van der Zwaan et al., 1990; van Hinsbergen et al., 2005). Generally, planktonic forms are the most abundant in the open marine environments. Thus, high percentages of planktonic foraminifera in the assemblages may indicate a long distance from the shore. On the other hand, benthic foraminifera, excluding infaunal forms (van der Zwaan et al., 1990), rely on organic matter that can reach the sea floor. Generally, less benthic foraminifera in the assemblages indicate greater depths. However, the benthic populations can be reduced due to low oxygen concentrations (Jorissen et al., 1995). This may influence the ratio of pelagic to benthic forms, but in the Hyżne section, there is no evidence of disturbances caused by oxygen changes.

The epipelagic/bathypelagic foraminiferal ratio (Fig. 8, Epi/Bathy), in addition to palaeobathymetric estimations, is useful for determining the offshore distance (Sliter, 1972; Sliter and Baker, 1972). The *r*-type strategies (*r*-selected) small-sized and simple morphotypes with globular bi-, triserial, planispiral or trochospiral chamber arrangements, such as heterohelicids, hedbergellids and globigerinelloidiids (Caron and Homewood, 1983; Petrizzo, 2002) are regarded as epipelagic and prefer near-surface water environments (<200 m). Such species have high reproductive potential and can be considered as indicators of unstable environments, whereas *K*-strategy (*K*-selected) specialist taxa, complex morphotypes, keeled and highly ornamented, e.g. globotruncaniids, are characterized by low reproductive potential. They can be considered as indicators of stable environments, and are believed to live as bathypelagic forms in the bathyal zone (>200 m) outside the continental shelf (Hart and Bailey, 1979; Hart, 1980; Caron and Homewood, 1983; Leckie, 1987; Hemleben et al., 1989; Petrizzo, 2002; BouDagher-Fadel, 2012; Schiebel and Hemleben, 2017).

The ratio of agglutinated to calcareous benthic forms can be a good indicator of sea-level changes, thus, the high percentages of agglutinated foraminifera (DWAF) in the assemblages may be connected with deepening of the environment (Cetean et al., 2011). Dominance of calcareous forms in the assemblages may be interpreted as a relative sea-level rise commonly associated with a transgression in the marginal part of the basin. During marine flooding, terrigenous siliciclastic material is harder to obtain for agglutinating foraminifera. This ratio of agglutinated to calcareous benthic foraminifera may also be connected with the ocean acidification that took place during the terminal Maastrichtian (Gasiński et al., 2012; Punekar et al., 2016). It is not precluded that the calcareous forms are affected by an acidic environment and are dissolved in the worst case.

The agglutinated tubular forms are regarded as suspension feeders (Jones and Charnock, 1985; Nagy, 1992). The increase in abundance of tubular forms (Sus. f./Other agg. Parameter) may signal high frequency of turbiditic currents and nutrient supply. Therefore, the suspension feeders/other agglutinated foraminifera ratio is a good indicator of organic carbon flux (OCF) in the flysch-type basins of high terrigenous influx (Kaminski and Kuhnt, 1995; Reolid et al., 2008).

In the assemblage of interval A1 (late Campanian, samples from the base of the profile (Hy13, Hy12, nannoplankton C 22 Zone) benthic foraminifera prevail. In sample Hy13, only benthic fauna is present and consists of both agglutinated and calcareous benthic foraminifera in similar amounts. Up in the profile, in sample Hy12, more calcareous benthic forms appear and bathypelagic forms dominate in the small population of planktonic species. In the same interval, agglutinated foraminifera drop in number, but they are mostly a suspension feeders morphotype. The dominance of such morphotype in the assemblage indicates a higher organic matter flux to the basin in the late Campanian.

Interval A2 (early late Maastrichtian, *A. mayaroensis* Zone, Hy11 to Hy7) shows fluctuations of the P/B ratio and a continuous dominance of epipelagic forms amongst planktonic foraminifera. Agglutinated forms are scarce almost throughout the entire A2 part of the profile. More agglutinated species are observed at the top of the interval, which are represented by two peaks on the Agg/Calc graph (samples Hn12, Hy7; Fig. 8).

*Abathomphalus mayaroensis* is observed in the association of interval A2 in keeled, *K*-strategy, bathypelagic species related to a stable environment and relatively deep-water conditions that are characteristic of open-marine waters (Smit, 1982). In the upper part of interval A2 and in the next interval B, the species diversity began to decline, the index taxon *A. mayaroensis* is no more observed and most of the bathypelagic planktonic foraminifera became extinct. Several reasons for the absence of *A. mayaroensis* and other bathypelagic forms (below the K-Pg boundary) can be invoked. The most possible explanation of the disappearance of *A. mayaroensis*, a bathypelagic form, is ecological instability referred to bathymetric and climatic changes. *A. mayaroensis* occurs deeper than the upper bathyal depths (Farouk, 2014 and references therein). Its disappearance corresponds with the latest Maastrichtian (66.8 Ma) eustatic sea-level drop by ~75 m, which was observed in the Western Tethys (Haq et al., 1988; Haq, 2014) and the Arabian Platform (Haq and Al-Qahtani, 2005). This change may have disturbed ecological

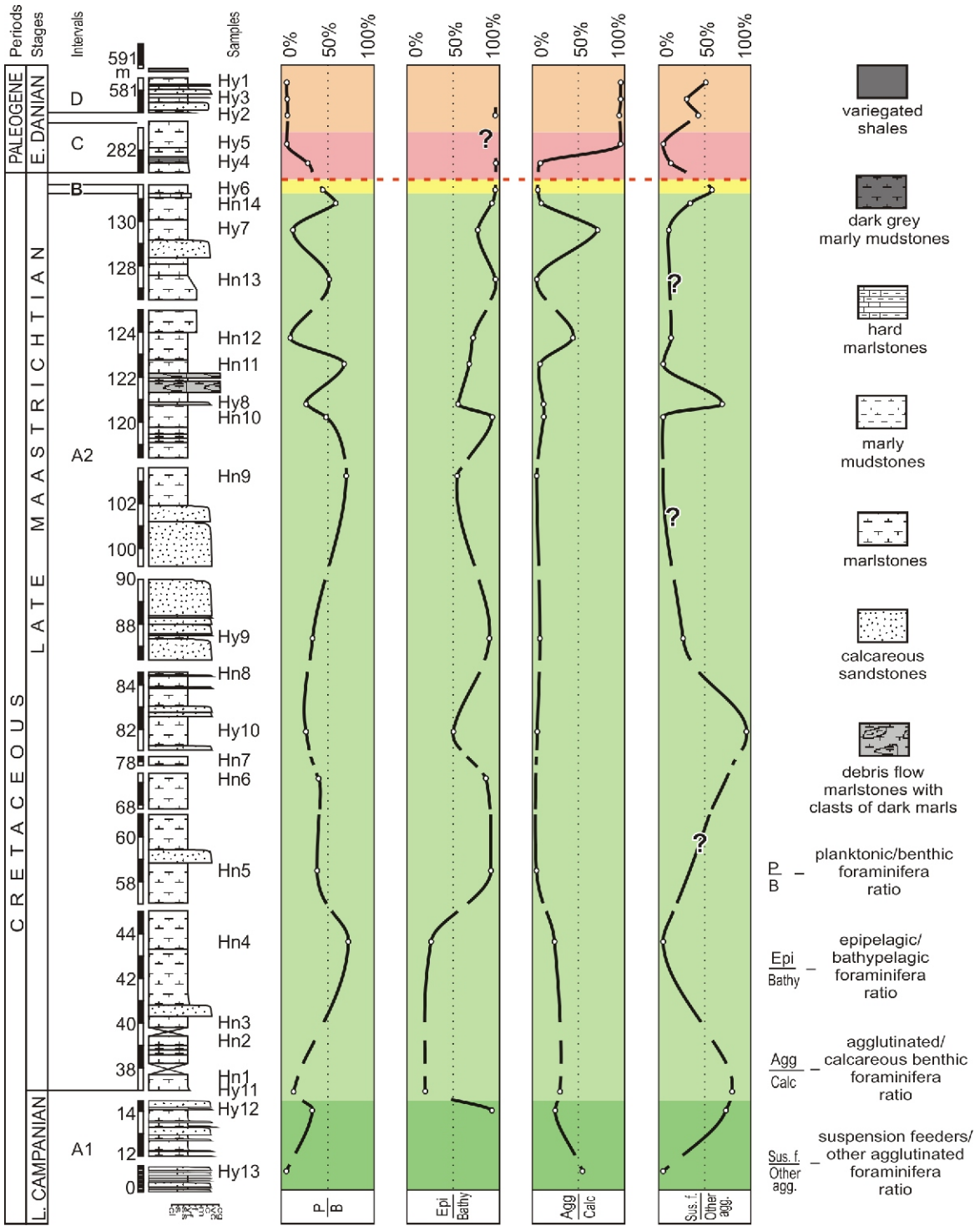


**Fig. 8. Quantitative analysis of foraminiferal assemblages of the studied samples**

conditions in the basin, and *A. mayaroensis* is referred to non-stable ecological conditions due to climatic changes that caused, e.g., rapid warming pulses (see Keller and Abramovich, 2009; Kędzierski et al., 2015). This agrees with the fact that most of the Cretaceous bathypelagic planktonic foraminifera went extinct at the K-Pg boundary (Keller, 2001; Keller et al., 2018). Our study shows the gradual turnovers of the Maastrichtian planktonic foraminifera below the K-Pg boundary. It started with disappearance of the largest and most specialized *K*-strategy dwellers of tropical to sub-tropical deep waters, such as *Abathomphalus, Contusotruncana, Globotruncanita* and *Globotruncanella*, followed by the less specialized, large, complex Heterohelicidae, such as *Racemiguembelina, Planoglobulina* and *Pseudotextularia*, and the trochospiral, ornamented *Rugoglobigerina* as the last one (Figs. 2 and 5; Table 1).

The K-Pg boundary mass extinction is commonly associated with the ocean acidification that was already observed in the other Skole Nappe sections (Gasiński et al., 2012). The tests of planktonic foraminifera from the top of interval A2 (sample Hy8, Table 1) and from interval B (sample Hy4, Table 1) show traces of dissolution. This may be interpreted as the result of the dissolution of shells due to sea acidification. The acidification event is related to the K-Pg boundary (Tyrrell et al., 2015 and references therein).

In the fine and small-sized fractions (<64 μm and 64–150 μm), a higher number of planktonic individuals is present and they are dominated by *Guembelitria*, *Heterohelix* and *Globigerinelloides*. The tests of planktonic foraminifera of intervals B and C and benthic calcareous foraminifera of interval C show a distinct decrease in size (Figs. 3J1–J5 and 4L, O, P). Larger forms are significantly more numerous in the older assemblages from intervals A1 and A2 (Fig. 4J and K). The morphological size reduction of foraminifera (the so-called Lilliput effect) as a response to environmental stress (Schmidt et al., 2004; Harries and Knorr, 2009; Keller and Abramovich, 2009; Keller et al., 2011b) is also an important feature of the K-Pg transition in the studied section.

The foraminifera from the fine fraction (<64 μm) of intervals B and C are characterized by a significant increase in abundance (bloom) of small, planktonic, opportunistic *Guembelitria cretacea*. This species is known to survive in environmentally unstable conditions of shelf or even shallower neritic areas, and it is characteristic of marginal seas (e.g., Kroon and Nederbragt, 1990). In the assemblage of interval C, the coeval bloom of calcareous benthic, infaunal *Bolivinita* sp. (*Bolivinita*-type) is observed. The *Bolivinita* sp. bloom in the New Zealand region took place in the outer shelf to bathyal depths, and the bathymetry is considered a major controlling factor of its stratigraphic distribution (Scott, 1965, 2017).

The investigated deposits show low diversity of foraminifera with dominance of two species constituting up to 70% of the total assemblage. The significant dominance of the opportunistic species (*r*-type strategies), represented by epipelagic planktonic *G. cretacea,* and shallow-water small species of calcareous benthic with thin tests, such as *Bolivinita* sp. (or *Bolivina*-type), usually indicates the high environmental stress (Frezza et al., 2005). The next important foraminiferal bioevent recorded in interval C, slightly above the K-Pg boundary, is that the benthic assemblage is dominated by calcareous epifaunal morphogroups belonging to *Cibicides* and *Brotzenella* (Peryt et al., 2002). A similar event has been noted in the same stratigraphical position in Tunisia, where the assemblages are also composed almost entirely of epifaunal species. The structure of the benthic foraminiferal assemblages and the faunal turnover are controlled by the food supply to the sea floor (cf. Peryt et al., 2002, 2004). The occurrence of the blooming *G. cretacea* and *Bolivinita*-type opportunistic species (and the very high ratio (>95%) of planktonic epipelagic/planktonic bathypelagic (epi/bathy), dissolved foraminiferal tests (Gasiński et al., 2012, 2013; Punekar et al., 2016), and the “Lilliput effect” of their tests (reduction in size) indicate stress environmental conditions during the *Guembelitria* first and *Guembelitria* second blooms that correspond to the CC 26 and NP1/2 calcareous nannoplankton zones in the studied section (Table 1).

In the fine (<64 μm) fractions of samples from the interval C (Hy4, Hy5), glass spherules can be observed (Table 1). The presence of glass spherules was also noted in the Bąkowiec section of the Skole Nappe (Dąbek and Wójcik-Tabol, 2018), in the same stratigraphical position. The spherules therein and in the Hyżne section may indicate that ejected dust has got into the sediment after the multiple impact events, e.g. Chicxulub impact, Deccan Traps. The glass spherules with nickel-rich spinel grains were recorded from the K-Pg boundary clay at Lechówka, Lublin Upland, SE Poland (Brachaniec et al., 2014). These events are related to the K-Pg boundary, which corresponds to the base of the so-called boundary clay with an anomalous iridium (Ir) concentration known worldwide (Molina et al., 2009; Schulte et al., 2010, and reference therein).

The response of foraminiferal assemblages to the K-Pg environmental stress was reflected in various bioevents. The palaeobathymetrical changes are manifested by diversity and abundance of foraminifera with specific depth requirements. At the base of interval A2, the bathypelagic planktonic forms are relatively diverse and common, but the assemblage is dominated by benthic species. Therefore, the assemblage of interval A2 may represent the upper bathyal zone. A gradual decrease in abundance of planktonic bathypelagic species and an increase in abundance of planktonic epipelagic species suggest a shallowing of depositional environment (Gasiński, 1997). The latest Maastrichtian is characterized by a decrease in bathypelagic and intermediate planktonic foraminifera and in species diversity (Keller, 2001). The sea shallowing may also be the reason for the absence of nannoplankton in many sections of the K-Pg boundary, but there are no signs of shallowing in the sedimentary record of investigated sections. The assemblages of the upper part of interval B and the lower part of interval C (directly above the K-Pg boundary) show a gradual decrease in abundance of epipelagic taxa until their complete disappearance at the top of interval C. In the Paleogene part of the section, the calcareous benthic taxa are less diverse or even absent (sample Hy5) and they are completely replaced by the agglutinated forms in the assemblage of interval D. This turnover is also observed in other K-Pg sections of the Skole Nappe (Gasiński and Uchman, 2011). In the uppermost part of the studied section (interval D, samples Hy1–Hy3), the foraminiferal assemblage indicates distinctly different environmental conditions. The most common taxa represent organic-cemented deep-water agglutinated foraminifera (DWAF; Kuhnt et al., 1989), e.g. *Glomospira*, *Hormosina*, *Paratrochamminoides* and *Recurvoides*. Tubular forms are rare in the assemblage of interval D. *Ammolagena clavata* is exceptionally abundant, which is regarded as an indicator of middle to lower bathyal settings above the carbonate compensation depth (CCD) and below the local foraminiferal lysocline and it has been described from high diversity foraminiferal assemblages of turbiditic deposits (Kaminski and Gradstein, 2005; Waśkowska-Oliwa, 2005; Waśkowska, 2014; Fontanier et al., 2008). Additionally, agglutinated foraminifera with calcareous cement, e.g. *Dorothia, Gaudryina*, *Arenobulimina,* occur in this foraminiferal assemblage. They confirm the depositional environment above CCD (e.g., Baliniak, 2018 and references therein). Along with agglutinated foraminifera, poorly preserved

single species of planktonic *Parasubbotina* cf. *pseudobulloides* and very rare calcareous benthic foraminifera *Cibicidoides* and *Gyroidinoides* occur. A similar composition of the foraminiferal assemblages was recorded in the lower Paleocene deposits of the Subsilesian Nappe (Waśkowska-Oliwa, 2005).

According to Haq (2014), the global eustatic sea level fell in the latest Maastrichtian and was followed by a sea-level rise in the late early Danian. The inferred relative sea-level changes in the investigated section reveal a good coincidence with the regional and eustatic sea-level changes during the Maastrichtian–early Danian (Haq et al., 1988; Hardenbol et al., 1998; Haq, 2014 and references therein). We have also noted that water-depth changes are only one possible cause of foraminiferal variation; other changes, such as temperature or food supply correlated with productivity, might be the proximate cause of variation in the composition of assemblages.

The analysis of the foraminifera assemblages, yielded from the investigated section, show a few peaks on the ratio curve, representing the content of suspension feeders (benthic agglutinated tubular forms such as *Nothia excelsa*, *Rhizammina indivisa*, *Rhabdammina cylindrical*). These peaks based on the high frequency of the suspension-feeding organism indicate an organic carbon flux (OCF) to the basin. Some of these increases in abundance of suspension feeders were observed in intervals A2 in *Abathomphalus mayaroensis* Zone in late Maastrichtian and above the K-Pg transition in the upper part of Zone P0 (see Fig. 8), what can be connected with of OCF in earliest Danian. This indicates fluctuations of organic matter flux to the marginal part of the Skole Basin floor in the studied time interval.

It must also be taken into consideration that some sedimentological signals of shallowing or deepening are not observed due to poor condition of the exposures. Foraminiferal tests are relatively well preserved, generally not fragmented or broken (despite the fact that the investigated deposits were transported by turbid currents from shallower zones). It also should be noticed that the prevailing part of the studied sediments was transported by turbiditic currents, which originated in shallower zones. Therefore, the palaeobathymetric interpretations based on the composition of foraminiferal assemblages are related more to their primary sedimentary environment than to the final depositional areas. Nevertheless, the changes in assemblages may express some bathymetric trends and sea-level dynamics in the marginal parts of the basin, which influences source material of the deposits. There are some peaks on the ratio curves (Fig. 8), which have been ignored in the interpretation because they are based on a too small number of specimens, e.g. the epi/bathy ratio peak at the top of the profile, caused by one epipelagic specimen in the entirely planktonic group, or the peaks in suspension feeders/other agglutinated (Sus. f./Other agg.), caused by, e.g., the occurrence of only one tubular foraminifera in the agglutinated assemblage or just a few specimens in total (Fig. 8). This situation may also be simply explained by redeposition or reworking of sediments in flysch-type basins.

The compositions of the Late Cretaceous foraminiferal planktonic assemblages (see previous chapter and Fig. 2) are characteristic of the "transitional zone" between the Tethyan (e.g., *Contusotruncana contusa*, *Globotruncana arca*, *G. bulloides*, *G. linneiana, Globotruncanita stuarti, Abathomphalus mayaroensis*) and Boreal (e.g., *Globigerinelloides prairiehillensis, Hedbergella holmdelensis, H. monmouthensis*, *Heterohelix globulosa*, *H. reussi*) biogeoprovinces (Gasiński, 1997, 1998). They are similar to the earlier described foraminiferal assemblages of the Ropianka Formation of the Skole Nappe (Gasiński and Uchman, 2009).

The examined assemblages contain a mixture of low-, middle- and high-latitude species of calcareous nannoplankton. The known high-latitude cool-water (Boreal Ream) indicators (Lees, 2002; Mutterlose et al., 2005; Thibault et al., 2012) include *Ahmuellerella octoradiata, Arkhangelskiella cymbiformis, Biscutum constans, Cribrosphaerella daniae, Kamptnerius magnificus, Lucianorhabdus cayeuxii, Nephrolithus frequens,* and *Prediscosphaera stoveri.* Warm-water taxa confined to low and middle palaeolatitudes of the Tethyan Realm (Thierstein, 1980; Perch-Nielsen, 1985) include *Watznaueria barnesae, Ceratolithoides aculeus, Eiffellithus* sp. and *Lithraphidites quadratus* (Figs. 6 and 7). This suggests a connection between the Tethyan and Boreal realms. The mixed character of the high- and low-latitude calcareous nannoplankton is typical of the Late Cretaceous in the Outer Carpathians (Švábenická, 2001; Jugowiec-Nazarkiewicz, 2007; Kędzierski et al., 2015) and it is observed in all the Late Cretaceous samples from the Hyżne section.

According to Thierstein (1980), *Micula staurophora* is a highly dissolution-resistant form and is considered a good indicator of poor nannofossil preservation and diagenetic enhancement. However, the investigated samples contain very few specimens of this taxon. Gardin and Monechi (1998) and Gardin (2002) suggested that the appearance of *Cruciplacolithus primus* marks the onset of the return to more stable environmental conditions after the perturbations at the K-Pg boundary. *Braarudosphaera* is a sporadic taxon in the studied samples, and no blooms of *Braarudosphaera* were observed. The blooms as well as the *Braarudosphaera* genera themselves are considered as indicators of shallow-water environments. The bloom is probably related to nutrient enrichment (Peleo-Alampay et al., 1999; Kelly et al., 2003). *Braarudosphaera bigelowii* seems to prefer marginal seas and eutrophic environments (Cunha and Shimabukuro, 1997).

## CONCLUSIONS

The detailed biostratigraphical study shows a nearly continuous record of the K-Pg transition in the Hyżne section. The changes of benthic and planktonic foraminifera and calcareous nannoplankton were influenced by a series of environmental crises recognized worldwide. Such a complete record of events and changes is unique in the northern margin of Tethys. The planktonic foraminiferal zones characterizing the late Maastrichtian-early Danian interval are present. They include:

- the standard *Abathomphalus mayaroensis* Zone *sensu* Caron (1985), which comprises bioevents of important stratigraphic significance: – the interval with *A. mayaroensis* occurrence; – the interval with a gradual disappearance of keeled and large racemiguembelinid taxa; – the interval with the *G. cretacea* first bloom;
- the *G. cretacea* second bloom Zone (P0 Zone) that corresponds to the nannofossil NP1/2 Zone, indicating the earliest Danian;
- the *P. pseudobulloides* (P1a) Zone that indicates the top of the early Danian.

The lower upper Maastrichtian foraminiferal assemblages are highly diverse, with taxa showing *K*-strategy and *r*-strategy, and well-preserved planktonic taxa with a mixture of epifaunal and infaunal benthic morphogroups suggesting a stable environment.

In the studied section, the mass extinction at the K-Pg boundary is recorded below the thin dark grey marly mudstones layer. The gradual disappearance of the Maastrichtian planktonic foraminifera below the K-Pg boundary, from the largest, most specialized, through less specialized large heteroheliciids

to the small simple *r*-strategy forms is observed. The gradual extinction of many Cretaceous species in the latest Maastrichtian characterizes most of the continuous K-Pg boundary sections, demonstrating the great complexity of various environmental changes. The K-Pg interval bioevents at the Hyżne section can be useful for better stratigraphic resolution of the Outer Carpathians. The *G. cretacea* second bloom (P0) Zone is characterized by blooms of opportunistic planktonic and benthic shallow infaunal foraminifera species and by low diversity of planktonic foraminifera. The benthic foraminifera are diverse and dominated by epifaunal taxa. The studied foraminiferal assemblages derive from different bathymetric zones. They can be referred to (1) the zone not deeper than the upper bathyal depths, above FL in the late Campanian and early late Maastrichtian, (2) a depth corresponding to the zone not deeper than the shelf margin during the latest Maastrichtian and earliest Danian, and (3) the middle-lower bathyal depth, below LF and above CCD, in the late early Danian. The relative sea-level changes inferred for the section reveal a good coincidence with the regional and global eustatic sea-level changes during the Maastrichtian–early Danian. However, the deposits of the section were transported mainly by turbiditic currents from shallower zones, and the bathymetric changes reflect the situation in the source area of the deposits, not necessarily in the final place of deposition. The mixed character of the high- and low-latitude calcareous nannoplankton, similarly to foraminifera, suggests a connection between the Tethyan and Boreal realms.

**Acknowledgments**. We are very grateful to V. Ćosović (Zagreb), D. Peryt (Warsaw) and L. Jankowski (Kraków) for their thorough reviews of this article, and to E. Malata, T. Peryt and K. Leszczyński for editorial and the English text improvement. The research was sponsored by the Jagiellonian University (Project No. N23/DBS/000011) and financially supported by the National Science Centre, Poland (No. UMO-2014/15/B/ST10/04229).

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